

# X-shaped radio galaxies as observational evidence for the interaction of supermassive binary black holes and accretion disk at pc scale

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Accepted \*\*\*. Received \*\*\*; in original form \*\*\*

## ABSTRACT

In the hierarchical galaxy formation model, today’s galaxies are the product of frequent galaxy merging, triggering the activity of active galactic nuclei and forming a supermassive black hole binary. A binary may become stalling at pc-scale and is expected to be detected in nearby normal galaxies, which is inconsistent with observations. In this paper, we investigate the interaction of the supermassive binary black holes (SMBBHs) and an accretion disk and show that the stalling can be avoided due to the interaction and a rapid coalescence of SMBBHs can be reached. A binary formed during galaxy merging within Hubble is most likely inclined with a random inclination angle and twists the accretion disk, aligning the inner part of the disk with the orbital plane on a time scale  $\sim 10^3$  yr. The twisted inner disk subsequently realigns the rotating central supermassive black hole on a time scale  $\lesssim 10^5$  yr due to the Bardeen-Peterson effect. It is shown that the detected X-shaped structure in some FR II radio galaxies may be due to the interaction-realignment of binary and accretion disk occurred within the pc scale of the galaxy center. The configuration is consistent very well with the observations of X-shaped radio sources. X-shaped radio feature form only in FR II radio sources due to the strong interaction between the binary and a standard disk, while the absence of X-shaped FR I radio galaxies is due to that the interaction between the binary and the radiatively inefficient accretion flow in FR I radio sources is negligible. The detection rate,  $\lambda_X \sim 7\%$ , of X-shaped structure in a sample of low luminous FR II radio galaxies implies that X-shaped feature forms in nearly all FR II radio sources of an average lifetime  $t_{\text{life}} \sim 10^8$  yr. This is con-

sistent with the estimates of net lifetime of QSO and radio galaxies and with the picture that the activity of active galactic nuclei is triggered by galaxy merging. As the jet orients vertically to the accretion disk which is supposed to be aligned with galactic plane of host galaxy, the old wings in X-shaped radio sources are expected to be aligned with the minor axis of host galaxy while the orientation of the active jets distributes randomly. It is suggested by the model that the binary would keep misaligned with the outer disk for most of the disk viscous time or the life time of FR II radio galaxies and the orientation of jet in most FR II radio galaxies distributes randomly. As the binary-disk interaction in FR I radio galaxies is negligible or a source evolves from FR II- to FR I-type after the binary becomes aligned with the outer disk, the jets in most FR I radio galaxies is expected to be vertical to the accretion disk and thus the major axis of host galaxy. We discuss the relationship of X-shaped and double-double radio galaxies (DDRGs) and suggest that all X-shaped radio sources would evolve into DDRGs after the coalescence of the SMBBHs and that most radio sources evolve from FR II- to FR I-type after an interruption of jet formation, implying that the average size of FR I radio sources is smaller than that of FR II radio galaxies. The model is applied to two X-shaped radio sources 4C+01.30 and 3C293 and one DDRG source J0116-473 with a bar-like feature and show that the SMBBHs in the three objects are minor with mass ratio  $q \sim 0.1 - 0.3$ .

**Key words:** accretion, accretion discs – black hole physics – gravitational waves – galaxies: active – galaxies: interactions – galaxies: jets

## 1 INTRODUCTION

Recent observations show that all galaxies with bulges harbor a supermassive black hole (SMBH) of mass tightly correlating with both the mass and the velocity dispersions of the bulge (Ferrarese & Merritt 2000; Gebhardt *et al.* 2000; Magorrian *et al.* 1998; McLure & Dunlop 2002; Tremaine *et al.* 2002). This implies that one event is responsible for both the formations of the bulges and the central SMBH.

In hierarchical galaxy formation models, present-day galaxies are the product of successive minor mergers (Kauffmann & Haehnelt 2000; Haehnelt & Kauffman 2000; Menou *et al.* 2001), triggering the star-bursts and the activity of active galactic nuclei (AGNs) (Wilson & Colbert

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1995). The configuration is supported by the observations of compact steep-spectrum objects (CSSs) and gighertz-peaked sources (GPSs) which are most likely infant AGNs of age  $t \lesssim 10^5$  yr and show distortion of host galaxy, double nuclei, galaxy-interaction or close companion among about fifty per-cent of them (O’Dea 1998). In galaxy mergers, the two SMBHs at the galaxy centers become bound due to dynamical friction at a separation  $a$  of two SMBHs,  $a \sim 1 - 10$  pc, and become hard at a separation  $a_h \sim 0.01 - 1$  pc when the loss of the orbital angular momentum is dominated by three-body interactions between SMBBHs and the stars passing by and a loss cone forms (Begelman et al. 1980; Quinlan & Hernquist 1997; Yu 2002; Makino & Funato 2003). The decay time scale of the binary orbit is then propotional to the relaxation timescale of the parent galaxy longer than the cosmological time and the SMBBHs become stalling at  $a \sim a_h$ . Therefore, it is expected to detect SMBBHs in many nearby normal galaxies or AGNs. However, efforts to detect long-lived SMBBHs in normal galaxies are failed (Haehnelt & Kauffman 2002) and SMBBHs may be detected only in a handful AGNs, e.g. OJ287 (Sillanpää *et al.* 1988; Liu & Wu 2002), ON231 (Liu *et al.* 1995b), PKS1510-089 (Xie *et al.* 2002), MKN421 (Liu *et al.* 1997), NGC6260 (Komossa *et al.* 2003), and 3C66B (Sudou *et al.* 2003) (for a review of observations of SMMBHs, see Komossa (2003)). Liu *et al.* (2003) suggest that SMMBHs in FR II radio galaxies merger during FR II-active phase, leading to the formation of DDRGs. Many stellar dynamical mechanisms have been invoked to extract the angular momentum in literature (for a review, see Milosavljevic & Merritt (2002)) and found to be inefficient, including black hole wandering (Chatterjee *et al.* 2003), stellar slingshot effects and re-filling of the loss cone (Zier & Biermann 2001), and the Kozai mechanism (Blaes *et al.* 2002). This is the so-called *final parsec problem* (Milosavljevic & Merritt 2002).

Gas in merging galaxies is driven to the center on a time scale  $t_g \approx 10^8$  yr and triggers the star-bursts and AGN activity (Gaskell 1985; Hernquist & Mihos 1995; Barnes & Hernquist 1996; Barnes 2002), forming an accretion disk around central SMBH and of size as large as  $r_d \sim 10$  pc (Jones *et al.* 2000) and in general  $r_d \sim 10^4 r_G \sim 0.01 - 1$  pc (Collin & Hure 2001), where  $r_G$  is the Schwarzschild radius of central black hole. Therefore, it is expected that the secondary interacts with the accretion disk whenever a binary becomes hard. The interaction of an accretion disk and a binary is intensively investigated in literature (e.g. Lin & Papaloizou (1986); Artymowicz & Lubow (1994); Ivanov *et al.* (1998, 1999); Gould & Rix (2000); Armitage & Natarajan (2002); Narayan (2000); Liu *et al.* (2003)). If an accretion disk is standard, initially inclined SMBBHs warp, twist and align the accretion

disk within some radius  $r_{\text{al}} > a$  (Ivanov *et al.* 1999). Then, the orbital plane slowly becomes aligned with the outer disk of  $r > r_{\text{al}}$  due to exchange of angular momentum with accreting gas on a time scale depending on the total disk mass. When the orbital plane completely becomes coplanar with the outer accretion disk, the secondary opens a gap in the disk and losses its angular momentum via viscosity torque and in-spiraling on a viscous time scale (Lin & Papaloizou 1986; Armitage & Natarajan 2002). When the loss of orbit angular momentum due to gravitational wave radiation becomes dominated at  $a \lesssim 10^2 r_{\text{G}}$ , the secondary removes mass of the inner disk and mergers into the primary, leading to the interruption of jet formation (Liu *et al.* 2003),

Liu *et al.* (2003) identify DDRGs with objects in which the coalescence of SMBBHs and the removal of inner disk occurred. Although the observations of DDRGs are consistent the scenario, Merritt & Ekers (2002) suggest that binary coalescence leads to a spin-flip of central SMBH and forms X-shaped radio galaxies. So, the important question is which picture is correct or, if both are correct, what the relationship between DDRGs and X-shaped radio sources is. As there are several difficulties with the Merritt & Ekers' configuration (see the discussions in Sec. 4.2), we show in this paper that the mechanism to form the X-shaped feature detected in some FRII radio galaxies may be the interaction between the binary and an standard accretion disk at pc scale and that X-shaped feature and double-double lobes forms in different evolution phases of SMBBHs in FRII radio galaxies.

We investigate the interaction of SMBBHs and an accretion disk at pc scale and the reorientation of spin axis of rotating central SMBH and compare this configuration with the observations of X-shaped radio galaxies, which are consistent with each other. In this scenario, the FRII character of X-shaped radio galaxies is due to that the accretion disk is an standard  $\alpha$ -disk in FRII radio sources, while in FRI radio galaxies the accretion flow is radiatively inefficient ADAFs and the interaction of an ADAF and a binary is negligible. Basing on this scenario, we predicate that the orientations of active radio jets distribute randomly in FRII radio galaxies and are preferentially vertical to the major axis of host galaxies in FRI radio sources. The model also suggests that radio jets are aligned with the minor axis of host galaxies in DDRGs.

In the paper, we discuss the initial conditions of the binary-disk system basing the Bardeen-Peterson effect and specify the SMBBH system in Sec. (2). The interaction of accretion disk and inclined SMBBHs is investigated in detail in Sec. 3. In this section, we pay our special attention to the reorientations of the binary orbit and rotating central SMBH.

In Sec. 4, we discuss the connection between X-shaped radio galaxies and the objects in which the reorientation of spin axis of rotating central SMBH due to disk-binary interaction occurred. All the observations of X-shaped radio sources are discussed basing on the scenario. We also discuss the distribution of orientations of wings and active jets in X-shaped and normal radio galaxies in this section. The important question what is the relationship between DDRGs and X-shaped radio sources is addressed in Sec. 5. Our discussions and conclusions are presented in Sec. 6.

## 2 FINAL PARSEC PROBLEM OF THE BINARY EVOLUTION AND THE FORMATION OF DISK-SMBBH SYSTEM

### 2.1 Bardeen-Peterson effect and alignment of rotating SMBBH and inclined accretion disk

When the part of cold gas with low angular momentum loses its angular momentum due to viscosity and flows in-wards toward the central SMBH, an accretion disk and relativistic jets form (Shlosman *et al.* 1990; Barnes 2002). As the formed accretion disk keeps the angular momentum of gas, it is nearly aligned with the galactic gas disk, if no strong torque is exerted on it. Since all young AGNs with newly born relativistic jets of age have FR II radio morphologies (O’Dea 1998; Murgia *et al.* 2002; Perucho & Martí 2002), the accretion disk has an accretion rate  $\dot{m} \equiv \dot{M}/\dot{M}_{Edd} = L/L_{Edd} \gtrsim \dot{m}_{FR} = 6 \times 10^{-3}$  (Ghisellini & Celotti 2001; Cavaliere & D’Elia 2002; Maraschi & Tavecchio 2003) and is a standard  $\alpha$ -disk if  $\dot{m} \lesssim 1$  (Shakura & Sunyaev 1973) or slim disk for  $\dot{m} \gtrsim 1$  (Abramowicz *et al.* 1988). Here,  $\dot{M}_{Edd} = L_{Edd}/\epsilon c^2 = 2.30 M_8 (M_\odot \text{ yr}^{-1})$  for  $\epsilon = 0.1$  is the Eddington accretion rate (note the different definitions of Eddington accretion rate),  $\epsilon = 0.1 \epsilon_{-1} = L/\dot{M} c^2$  is the conversion rate of accretion mass to energy and  $M = M_8 \times 10^8 M_\odot$  is the mass of central SMBH.

For a gas-pressure dominated standard  $\alpha$ -disk, the ratio  $\delta$  of the half thickness  $H$  of accretion disk and radius  $r$  is

$$\begin{aligned} \delta &\equiv \frac{H}{r} \\ &\simeq 2.8 \times 10^{-3} \alpha_{-2}^{-1/10} \dot{m}_{-1}^{1/5} M_8^{-1/10} x_4^{1/20}, \end{aligned} \quad (1)$$

where  $\alpha_{-2} = \alpha/0.01$ ,  $\dot{m}_{-1} = \dot{m}/0.1$ ,  $x_4 = r/10^4 r_G$  and  $r_G = 2GM/c^2 = 2.97 \times 10^{13} M_8 \text{ cm}$  is the Schwarzschild radius. Such a gas-pressure dominated disk has a surface mass density

$$\Sigma \simeq 4.0 \times 10^5 \alpha_{-2}^{-4/5} \dot{m}_{-1}^{3/5} M_8^{1/5} x_4^{-3/5} \text{ g cm}^{-2} \quad (2)$$

and a total mass within the disk radius  $r_d$

$$M_d = \frac{10\pi}{7} \Sigma r_d^2 \simeq 7.92 \times 10^7 \alpha_{-2}^{-4/5} \dot{m}_{-1}^{3/5} M_8^{11/5} x_4^{7/5} M_\odot. \quad (3)$$

The disk radius  $r_d$  is empirically (Collin & Hure 2001)

$$\begin{aligned} r_d &\approx 2 \times 10^4 M_7^{-0.46} r_G \\ &\simeq 7 \times 10^3 M_8^{-0.46} r_G. \end{aligned} \quad (4)$$

However, accretion disk is no longer gas-pressure dominated for  $r \lesssim 10^2 r_G$  and the disc opening angle is (Collin-Souffrin & Dumont 1990)

$$\delta \simeq 9.9 \times 10^{-3} \alpha_{-2}^{-1/10} \left( \frac{L}{0.1 L_{\text{Edd}}} \right)^{1/5} M_8^{-1/10} \epsilon_{-1}^{-1/5} x^{1/20}. \quad (5)$$

For an accretion disk in AGNs of a typical value  $\alpha \sim 0.03$ ,  $\delta < \alpha \ll 1$ . If the rotating central SMBH is misaligned with the accretion disk, the innermost part of the accretion disk becomes aligned with SMBH spin direction due to the Bardeen-Peterson effect (Bardeen & Petterson 1975) out to a disk radius  $r_{\text{BP}} \gg r_G$ . When the rotating SMBH exerts a torque on the accretion disk and aligns the innermost part of the disk with its spin, the same torque tends to align the spin of the SMBHs with the accretion disk (Rees 1978; Scheuer & Feiler 1996), depending on the transfer of warps in radial direction. For an accretion disk with  $\alpha > \delta$  in AGNs, warps transfer in a diffusive way. Papaloizou & Pringle (1983) show that taking into consider of the internal hydrodynamics of the disk the usual azimuthal viscosity  $\nu$  and the viscosity  $\nu_2$  in the vertical direction are different. The inward advection of angular momentum via  $\nu$  is rather accurately canceled by the outward viscous transport of angular momentum due to  $\nu_2$ , while the radial pressure gradients due to the warp set up radial flows, whose natural period resonates with the period of the applied force and therefore reaches large amplitude. Finally, the effective vertical viscosity is approximately given by  $\nu_2 = \nu/2\alpha^2$  (Papaloizou & Pringle 1983; Kumar & Pringle 1985), which is valid even for a significant warp (Ogilvie 1999). Thus, the transfer time-scale of warp in the accretion disk is

$$t_{\text{wp}} \simeq \frac{2r^2}{3\nu_2} = 2\alpha^2 t_v = 2 \times 10^{-4} \alpha_{-2}^2 t_v, \quad (6)$$

where

$$t_v = \frac{r}{v_r} = \frac{2r^2}{3\nu} = \frac{2}{3} \delta^{-2} \alpha^{-1} \Omega_K^{-1}, \quad (7)$$

where  $\Omega_K$  is the Keplerian angular velocity at radius  $r$  and  $v_r = 3\nu/2r$  is the flow velocity in radial direction.

Considering the difference of  $\nu_2$  and  $\nu$  and using the accretion disk models for AGNs computed by Collin-Souffrin & Dumont (1990), Natarajan & Pringle (1998) show that the Bardeen-Peterson radius out to which the inner accretion disk of  $L/L_{\text{Edd}} = \dot{m} > \dot{m}_{\text{cr}}$  is aligned with the rotating SMBH is

$$r_{\text{BP}} = 22a_*^{5/8}\alpha_{-2}^{3/4}\left(\frac{L}{0.1L_{\text{Edd}}}\right)^{-1/4}M_8^{1/8}\epsilon_{-1}^{1/4} \quad (8)$$

and the spin axis of a rotating SMBH becomes aligned with the accretion disk due to the Bardeen-Peterson effect on a time scale

$$t_{\text{al1}} = 3.6 \times 10^4 \text{ yr } a_*^{11/16}\alpha_{-2}^{13/8} \times \left(\frac{L}{0.1L_{\text{Edd}}}\right)^{-7/8} M_8^{-1/16}\epsilon_{-1}^{7/8}, \quad (9)$$

where  $a_*$  is the dimensionless spin angular momentum of the primary and  $L$  is the luminosity of AGNs. Eq. 9 shows that the realignment time-scale  $t_{\text{al1}}$  is nearly independent of the SMBH mass but sensitive to the parameter  $\alpha$ . For an AGN with a moderately rotating central black hole  $a_* \simeq 0.7$ , and typical parameters  $\alpha_{-2} = 3$ ,  $\epsilon_{-1} = 2$  and  $L \sim 0.3L_{\text{Edd}}$ , the realignment time scale is  $t_{\text{al1}} \simeq 1.1 \times 10^5 \text{ yr}$ . If we take a typical advance speed of radio lobes  $v_j \simeq 0.3c$  for a young AGN (Owsianik *et al.* 1999) (we assumed an accelerating cosmology with  $\Omega_\Lambda = 0.7$ ,  $\Omega_B = 0.3$  and  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$  throughout this paper except mention), the realignment takes place when the source has a largest linear size  $l_m \lesssim t_{\text{al1}}v_j \simeq 10 \text{ Kpc}$ . An AGN is detected with a GPS source if  $l_m < 1 \text{ Kpc}$  or a CSS source if  $l_m \lesssim 20 \text{ Kpc}$  (for  $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $q_0 = 0.5$ ) (O'Dea 1998). Therefore, dramatical distortion may be detected in some radio jets of CSSs and GPSs. When the realignment finishes, lobes randomly orient and jets close to the central nuclei are nearly vertical to the accretion disk.

## 2.2 The hardening of SMBBHs and the interaction of the secondary and an accretion disk

When the gas in merger galaxies with low angular momentum is driven into center and triggers the activity of AGNs, the two SMBHs at the two galaxy centers lose the angular momentum due to dynamic friction and become bound at a separation of the two black hole  $a \sim 1 - 10 \text{ pc}$  on a time scale (Merritt 2000)

$$t_{\text{bd}} \simeq \frac{r_e}{0.30} \frac{\sigma^2}{\sigma_g^3}, \quad (10)$$

where  $\sigma$  and  $\sigma_g$  are, respectively, the one-dimensional velocity dispersions of the larger (primary) and smaller (secondary) galaxies, and  $r_e \simeq 2.6 \text{ Kpc } (\sigma/200 \text{ Km s}^{-1})^3$  is the effective

radius of the larger galaxy. Relating the one-dimensional velocity dispersions  $\sigma$  to the mass of the central SMBH with the empirical tight relation (Tremaine *et al.* 2002)

$$\log(M/M_\odot) = 8.13 + 4.02 \log(\sigma/200 \text{ km s}^{-1}) \quad (11)$$

and from Eq. (10), we have

$$t_{\text{bd}} \simeq 2.0 \times 10^8 \text{ yr } M_8^{1/2.01} q_{-1}^{-3/4.02}, \quad (12)$$

where  $q \equiv m/M = 0.1q_{-1}$ . Eq. 12 implies that  $t_{\text{bd}} \sim t_g$  and is consistent with the observations of host galaxies of young AGNs that about 50 percent of the host galaxies contain double nuclei, interaction of galaxies or significant morphological distortions due to galaxy merging (O'Dea 1998).

From Eq. 12,  $t_{\text{bd}}$  is larger than the Hubble time  $t_{\text{Hubble}}$  when  $q < 5 \times 10^{-4} M_8^{2/3} (t_{\text{bd}}/10^{10} \text{ yr})^{-4/3}$ , which is consistent with the numerical galaxy dynamical calculations (Yu 2002). As we are interested only in those SMBBHs formed within Hubble time, we have

$$q > q_{\text{cr}} \simeq 5 \times 10^{-4} M_8^{2/3} \left( \frac{t_{\text{bd}}}{10^{10} \text{ yr}} \right)^{-4/3}. \quad (13)$$

Bound SMBBHs become hard at a separation of the two SMBHs (Quinlan 1996; Yu 2002)

$$\begin{aligned} a_{\text{h}} &= \frac{GmM}{4\sigma^2(m+M)} \\ &= 6.5 \times 10^3 M_8^{-1/2.01} \left( \frac{q}{0.02} \right) (1+q)^{-1} r_{\text{G}} \end{aligned} \quad (14)$$

on a time scale  $\lesssim t_{\text{bd}}$  due to dynamic friction. A hard binary loses orbital angular momentum via stellar dynamic interaction on a time scale maybe much longer than the Hubble time (Begelman et al. 1980; Quinlan 1996; Yu 2002) (for more discussion, see Sec. 1). However, Eqs. 4 and 14 show that  $a_{\text{h}} \lesssim r_{\text{d}}$  for a minor merger with  $q \lesssim 0.3$  and the binary interacts with the accretion disk soon after it becomes hard. As the interaction between the SMBBHs and a standard accretion disk is very efficient in hardening SMBBHs, the *final parsec problem* can be avoided. We investigate in detail the interaction between the SMBBHs and an accretion disk in following sections.

When the orbital radius  $a$  is very small, the loss of angular momentum of the SMBBHs due to gravitational radiation becomes important. When  $a$  is smaller than a critical radius  $a_{\text{cr}}$ , the loss of angular momentum due to gravitational radiation becomes dominated with respect to binary-disk interaction. Liu *et al.* (2003) show

$$a_{\text{cr}} = \frac{1}{2} \left( \frac{128}{15} \right)^{2/5} \delta^{-4/5} \alpha^{-2/5} q^{2/5} (1+q)^{1/5} f^{2/5} r_{\text{G}}, \quad (15)$$



where  $f$  is a function of the binary eccentricity  $e$ :

$$f = \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) (1 - e^2)^{-7/2}. \quad (16)$$

From Eqs. 14, 15 and 1, the interaction between binary and accretion disk is always important only if

$$q > 6.0 \times 10^{-5} M_8^{29/30} \alpha_{-2}^{-8/15} \dot{m}_{-1}^{-4/15} x_2^{-1/15} f^{2/3}, \quad (17)$$

where  $x_2 = r/10^2 r_G$ . Therefore, the interaction of the accretion disk and the SMBH plays a very important role in the evolution of SMBBHs with  $q > 5 \times 10^{-4} M_8^{2/3} (t_{\text{bd}}/10^{10} \text{ yr})^{-4/3}$ .

### 3 THE ALIGNMENT OF ACCRETION DISK WITH ORBITAL PLANE AND THE REORIENTATION OF CENTRAL ROTATING SMBH

#### 3.1 Accretion modes in AGNs

Although the accretion disk in young AGNs is most likely a standard thin- or slim-disk, the accretion rate may have decreased significantly when the binary becomes hard and interacts with the accretion disk. When the secondary SMBH enters the accretion disk with a random inclination angle, it interacts with the disk in two regimes: direct collisions and long-ranged interaction. The interaction between a companion star and the accretion disk around a primary has been investigated intensively in literature (e.g. Ivanov *et al.* (1998, 1999); Lin & Papaloizou (1986); Narayan (2000)) and the effects of the interaction depends on accretion modes and disk total mass.

If the accretion rate  $\dot{m}$  of a disk is lower than a critical rate  $\dot{m}_{\text{cr}} \sim 10^{-2} - 10^{-1}$ , the inner disk or the whole accretion disk becomes, probably via disk evaporation (Meyer & Meyer-Hofmeister 1994; Liu *et al.* 1995a; Meyer *et al.* 2000), radiatively inefficient advection dominated accretion flows (ADAFs) (Narayan & Yi 1994; Abramowicz *et al.* 1995), advection dominated inflow and outflow (ADIOS) (Blandford & Begelman 1999), or convection dominated accretion flows (CDAFs) (Narayan *et al.* 2000). Narayan & Yi (1995) and Esin *et al.* (1997) show that if the fraction of viscously dissipated energy advected is  $f \simeq 1$ , the transitional accretion rate is  $\dot{m}_{\text{cr}} \sim 1.3 \alpha_{\text{AD}}^2$ , where  $\alpha_{\text{AD}}$  is the viscous parameter of the radiatively inefficient accretion flow. Both dynamical investigation (Liu & Wu 2002) and spectrum fit (Esin *et al.* 1997; Quataert & Narayan 1999) show that  $\alpha_{\text{AD}}$  is typically between 0.3 and 0.1. As the critical accretion rate corresponds to the transition from a radiation dominated regime of  $f \simeq 0$  to advection dominated accretion of  $f \simeq 1$ , it is expected that  $0 < f < 1$  and  $\dot{m}_{\text{cr}}$

critically depends on the physical process in the disk. Mahadevan (1997) shows

$$\begin{aligned}\dot{m}_{\text{cr}} &= 7.8 \frac{(1-f)}{f} \frac{(1-\beta)}{\beta} \alpha_{\text{AD}}^2 c_1^2 \frac{1}{g(\theta_e)} \\ &\simeq 0.28 \alpha_{\text{AD}}^2,\end{aligned}\tag{18}$$

where  $\beta$  is the ratio of gas pressure to total pressure,  $c_1 \simeq 0.5$ , and  $g(\theta_e)$  is a function of electron temperature with  $g(\theta_e) \sim 7$ . In computing Eq. (18), Mahadevan (1997) takes  $f \sim 0.5$  and  $\beta \sim 0.5$ , which is consistent with the recent suggestion that the transition most likely occur at the region where radiation pressure becomes important. If the FR transition of radio galaxies corresponds to the transition of accretion mode  $\dot{m}_{\text{FR}} \simeq 6 \times 10^{-3}$  implies that the typical viscous parameter in FRI radio galaxies is  $\alpha_{\text{AD}} \simeq 0.15$ . Accretion disk is believed to be thin (Shakura & Sunyaev 1973) for  $1 \gtrsim \dot{m} \gtrsim \dot{m}_{\text{cr}}$  and slim (Abramowicz *et al.* 1988) when  $\dot{m} \gtrsim 1$ .

### 3.2 Interaction between SMBBHs and standard thin disks

As the outer part of an accretion disk with  $r \gtrsim 10^2 r_{\text{G}}$  is most possibly a gas pressure-dominated standard disk, we first explore its interaction with SMBBHs. From Eqs. (3) and (4), we obtain the ratio  $\eta$  of the disk total mass and the mass of the secondary

$$\begin{aligned}\eta &\equiv \frac{M_{\text{d}}}{m} \\ &\approx 5q_{-1}^{-1} \alpha_{-2}^{-4/5} \dot{m}_{-1}^{3/5} M_8^{0.556}.\end{aligned}\tag{19}$$

For those AGNs or QSOs with super Eddington accretion  $\dot{m} \gtrsim 1$ ,  $\eta$  is always greater than unit for any central BH masses in the range from  $10^6 M_{\odot}$  to  $10^{10} M_{\odot}$  (Wu *et al.* 2002). For a minor merger with mass ratio  $q < 0.3$  and of a standard thin disk of accretion rate  $\dot{m} > \dot{m}_{\text{cr}} \sim 10^{-2} - 10^{-1}$ ,  $M_{\text{d}} \gtrsim m$ .

When the secondary enters the accretion disk with a radius  $a \simeq r_{\text{d}}$ , the disk mass  $M_{\text{b}}$  contained inside its orbit is  $\sim M_{\text{d}}$  and  $M_{\text{b}} \sim \eta m \gtrsim m$  and the interaction between the secondary and accretion disk is dominated by BH-disk direct collisions and the distortion of the accretion disk due to the long range interaction of the secondary is small (Ivanov *et al.* 1998, 1999). Ivanov *et al.* (1998) and Vokrouhlicky & Karas (1998) show that during each direct collision an amount of gas of mass  $\sim \pi \Sigma r_{\text{a}}^2$  is accreted by the secondary and another amount of approximately the same mass gets velocities larger than the escape velocity in the SMBBH potential and leaves the system, where the accretion radius  $r_{\text{a}}$  of the secondary is

$$r_a = \frac{2Gm}{v_{\text{rel}}^2} \sim \frac{2Gm}{v_K^2} = 2qr \quad (20)$$

and  $v_{\text{rel}} \sim v_K$  is the velocity of the secondary relative to the disk gas. The outflow rate of the mass due to the direct collision is

$$\dot{M}_{\text{out}} \sim 2 \times \frac{2\pi\Sigma r_a^2}{t_{\text{orb}}} = 2\Sigma r_a^2 \Omega_K. \quad (21)$$

The disk drag to the secondary is important only when the outflow is compensated by the radial inflow of mass, i.e.  $\dot{M}_{\text{out}} < \dot{M} = 3\pi\nu\Sigma = 3\pi\alpha\delta^2 r^2 \Omega_K \Sigma$ , which implies

$$\begin{aligned} q < q_0 &= \sqrt{\frac{3\pi}{8}} \alpha^{1/2} \delta \\ &\simeq 3 \times 10^{-4} \alpha_{-2}^{2/5} \dot{m}_{-1}^{1/5} M_8^{-1/10} x_4^{1/20}. \end{aligned} \quad (22)$$

Eqs. (13) and (22) suggest that for SMMBHs with  $q > q_{\text{cr}}$  formed during galaxy merging within Hubble time the depleted region by the secondary cannot be sufficiently refilled with gas and its surface density is thus much less than the unperturbed value. The secondary would lose its angular momentum and migrates inwards on accretion time-scale  $\sim t_{\text{acc}}$  (Ivanov *et al.* 1999)

$$t_{\text{acc}} \equiv \frac{m}{\dot{M}} = \frac{q}{\dot{m}} t_s = 4.5 \times 10^7 \text{ yr } q_{-1} \dot{m}_{-1}^{-1}, \quad (23)$$

where  $t_s \equiv M/\dot{M}_{\text{Edd}} = 4.5 \times 10^7 \text{ yr}$ .

When the secondary migrates toward the mass center of binary and has a orbital radius  $a$  less than a critical radius  $a_m$  within which the disk mass  $M_b$  is equal to its mass  $m$ , the long-ranged averaged quadrupole component of the binary gravitational field becomes important and warps the disk first in the vicinity of the orbit (Lin & Papaloizou 1986; Ivanov *et al.* 1999; Kumar 1990). From Eq. (3), we have

$$a_m = 2.3 \times 10^3 q_{-1}^{5/7} \alpha_{-2}^{4/7} \dot{m}_{-1}^{-3/7} M_8^{-6/7} r_G \quad (24)$$

and  $a_m \gg r_{\text{BP}}$ . The twist and warp transfers both inwards and outwards. Numerical simulation given by Ivanov *et al.* (1999) shows that the inner accretion disk evolves into a quasi-stationary twisted configuration and becomes coplanar with the binary orbital plane for any value of  $\alpha$  (Ivanov *et al.* 1999). The alignment time scale  $t_{\text{al2}}$  is the warp transfer time scale  $t_{\text{tw}}$  and for an accretion disk with  $\alpha > \delta$  the transfer is radiative with

$$t_{\text{al2}} \simeq 3.0 \times 10^3 \text{ yr } \alpha_{-2}^{6/5} \dot{m}_{-1}^{-2/5} M_8^{6/5} x_3^{7/5}, \quad (25)$$

where  $x_3 = a/10^3 r_G$ . To obtain Eq. (25), we have used Eq. (6), (7) and (1). For an accretion disk with  $\alpha < \delta$ , the transfer is wave-like (Ivanov *et al.* 1999) and the time scale  $t_{\text{al2}}$  is

$\sim a/c_s \simeq \delta^{-1} \Omega_K^{-1} \sim 1.4 \text{ yr} \delta^{-1} x_3^{3/2} M_8$ . However, the innermost region of the aligned disk in the vicinity of the primary SMBH with  $r \lesssim r_{\text{bp}}$  is twisted and aligned with the rotating central SMBH due to the Bardeen-Peterson effect. The rotating SMBH becomes nearly coplanar with the binary orbital plane on another time scale  $t_{\text{al1}} \sim 10^4 \text{ yr} \gtrsim t_{\text{al2}}$  only if the binary orbital angular momentum  $J_b = amv_b \simeq m(GMa)^{1/2}$  is larger than the rotation angular momentum  $J_{\text{BH}} = a_* GM^2/c$  of the central black hole. Taking  $a \sim a_m$ , we have

$$\frac{J_b}{J_{\text{BH}}} \simeq 6.8 \times 10^2 \left( \frac{a_*}{0.1} \right)^{-1} q_{-1}^{19/14} \alpha_{-2}^{2/7} \dot{m}_{-1}^{-3/14} M_8^{-3/7}, \quad (26)$$

which gives  $J_b > J_{\text{BH}}$  for

$$q \gtrsim 8 \times 10^{-4} \left( \frac{a_*}{0.1} \right)^{14/19} \alpha_{-2}^{-4/19} \dot{m}_{-1}^{3/19} M_8^{6/19} \sim q_{\text{cr}}. \quad (27)$$

Eq. (27) implies that *the spin axis of the central SMBH formed during galaxy merging within Hubble time change its orientation from vertical to the outer accretion disk to well aligned with the rotation axis of the binary on a time scale  $t \lesssim 10^5 \text{ yr}$* . As the inclination angle of binary plane is random, the angle of the spin axis of the central SMBH relative to the galactic plane distributes randomly.

When the secondary interacts with the accretion disk and distorts the inner disk, it also twists and warps the accretion disk outside its orbit to some radius  $r_{\text{al}}$ , as the quadrupole contribution to the potential causes the precession of the major axis of an elliptical orbit with frequency (Ivanov *et al.* 1999)

$$\Omega_{\text{ap}} = \frac{3}{4} q \left( \frac{a}{r} \right)^2 \Omega_K, \quad (28)$$

where  $\Omega_K$  is the Keplerian angular velocity at  $r$ . The radius  $r_{\text{al}}$  out to which the disk is aligned with the orbital plane depends on the quadrupole component of the binary gravitational field and the transfer of warp and angular momentum in the disk, and can be estimated simply, assuming that at the radius  $r_{\text{al}}$  the time scale for radial transfer of the warp,  $t_{\text{warp}}$ , is on the order of the local quadrupole precession time scale  $\Omega_{\text{ap}}^{-1}$ . From  $t_{\text{wp}} = \Omega_{\text{ap}}^{-1}$  and Eq. (6), we have

$$r_{\text{al}} \sim (q\alpha)^{1/2} \delta^{-1} a \quad (29)$$

for an accretion disk with  $\alpha > \delta$  and diffusive-like transfer of disk warp, or

$$r_{\text{al}} \sim \frac{3^{1/2}}{2} q^{1/2} \delta^{-1/2} a \quad (30)$$

for a disk with  $\alpha < \delta$  and wave-like transfer of disk warp of  $t_{\text{wp}} \sim r/c_s$ . The realignment radius  $r_{\text{al}}$  given by Eq. (29) or (30) is exactly the same as the one given by Ivanov *et al.*

(1999) and Kumar (1990). To have the alignment scale larger than the binary orbit radius, we need

$$q > 5 \times 10^{-4} \alpha_{-2}^{-6/5} \dot{m}_{-1}^{2/5} M_8^{-1/5} x_3^{1/10}. \quad (31)$$

Here we have used Eq. (1) to obtain Eq. (31). Eqs. (13) and (31) suggest that for any SMBBHs-disk system formed during galaxy merging within Hubble time the secondary always aligns the accretion disk gets from the vicinity of the primary SMBH out to a radius  $r_{\text{al}} > a$ . If accretion disk is a slim disk with  $\dot{m} \gtrsim 1$  and  $\delta \sim 1 > \alpha$ , Eq. (30) implies  $q \gtrsim \frac{4}{3} \delta \sim 1$  for  $r_{\text{al}} > a$ . Therefore, only major merger can twist and align a slim disk.

### 3.3 Interaction between SMBBHs and ADAFs

As for an ADAF the accretion gas has a quasi-spherical morphology with  $\delta \sim 1$  and the orbital velocity  $v_\phi$  of the gas is significantly sub-Keplerian, the interaction between the secondary and the accretion flow is insensitive to the inclination of the orbit relative to the angular momentum vector of the accreting gas.

As an ADAF has  $\delta(\sim 1) > \alpha$ , transfer of its any distortion (warp and twist) is wave-like (Papaloizou & Lin 1995; Musil & Karas 2002). As the accretion flow has a very low accretion rate and is quasi-spherical, its warp and twist due to interaction with the secondary is negligible. The drag of the accretion flow to the secondary SMBH can be approximated with the interaction of a uniform gas of density (Narayan 2000)

$$\rho = \frac{\dot{M}}{4\pi r^2 v_r} \simeq \frac{\dot{m} \dot{M}_{\text{Edd}}}{4\pi r^2 \alpha_{\text{AD}} V_K}. \quad (32)$$

As the moving SMBH has a relative velocity  $|\vec{v}_{\text{rel}}| \sim v_K$  to the gas, the drag force is (Ostriker 1999)

$$F_{\text{df}} = -4\pi I \left( \frac{Gm}{v_{\text{rel}}} \right)^2 \rho, \quad (33)$$

where the coefficient  $I$  depends on the Mach number  $M \equiv v_{\text{rel}}/c_s$  and  $c_s$  is the sound velocity. As in our problem,  $v_{\text{rel}} \sim V_K \gtrsim c_s$  with  $M \gtrsim 1$  and  $I$  is approximately (Ostriker 1999; Narayan 2000)

$$I \sim \ln(R_{\text{max}}/R_{\text{min}}), \quad (34)$$

where  $R_{\text{max}} \sim H \sim r$  is the size of the system and  $R_{\text{min}}$  is the effective size of the secondary, which is approximately the accretion radius  $R_{\text{min}} \sim r_a = 2Gm/v_{\text{rel}}^2$ . Therefore, we have

$$I \sim \ln \left( \frac{rv_{\text{rel}}^2}{2Gm} \right) = \ln \left( \frac{M}{2m} \right) \simeq 2 - \ln q_{-1}. \quad (35)$$

Thus, the hydrodynamic drag time scale is

$$\begin{aligned} t_{\text{hd}} &\equiv \frac{mv_{\text{K}}}{|F_{\text{df}}|} \simeq \frac{\alpha_{\text{AD}}}{I\dot{m}} q^{-1} t_{\text{s}} \\ &\simeq 3 \times 10^9 \text{ yr } q_{-1}^{-1} \left( \frac{\alpha_{\text{AD}}}{0.15} \right) \dot{m}_{-2}^{-1}, \end{aligned} \quad (36)$$

where  $\dot{m}_{-2} = \dot{m}/10^{-2}$ . Therefore, the hydrodynamic drag of an ADAF on an orbiting SMBH is negligible.

When the secondary moves in an ADAF, some amount of gas is accreted and another approximately the same amount of mass obtains velocities greater than the escape velocity, as that in a standard thin disk (see Sec 3.2). Although it is different in ADAFs as the flow is significantly sub-Keplerian and  $\alpha_{\text{AD}} \sim 0.3$  and  $\delta \sim 1$ , Eq. (22) can give a reasonable lower estimate to the upper limit  $q_0$ . When  $q < q_0$ , the accretion flow can compensate the out flow due to the collision of the secondary and the accretion flow. Eq. (22) gives  $q_0 \sim \sqrt{\frac{3\pi}{8}} \alpha^{1/2} \delta \simeq 0.6$ . Therefore, the accretion flow can compensate the mass outflow due to the SMBBHs-disk collision even for a major merger.

### 3.4 Realignment timescale of the orbital plane and the outer disk and the lifetime of AGNs

When the twisted inner disk and the binary orbital plane become coplanar, the system stays quasi-stationary. As it is determined by the specific angular momentum of the gas entering the disk, the orientation of outer accretion disk with  $r > r_{\text{al}}$  is determined by the outer gas system and is supposed to be nearly aligned with that of the galactic disk. The gas in the accretion disk at  $r > r_{\text{al}}$  is accreting through the twisted disk and exchanges angular momentum with the binary, leading to the rotation axis of the aligned inner system slowly processing and realigning with that of the outer disk plane (Rees 1978; Ivanov *et al.* 1999), similar to the re-alignment of a rotating black hole with an inclined accretion disk due to the Bardeen-Peterson effect (Scheuer & Feiler 1996; Natarajan & Pringle 1998). The realignment time scale for a disk with  $\alpha \sim 1$  is (Ivanov *et al.* 1999)

$$t_{\text{al3}} \sim \frac{J_{\text{b}}}{\dot{J}_{\text{d}}} \simeq \frac{amv_{\text{b}}}{\dot{M}r_{\text{al}}v_{\text{d}}(r_{\text{al}})} \simeq \left( \frac{a}{r_{\text{al}}} \right)^{1/2} t_{\text{acc}} < t_{\text{acc}} \quad (37)$$

where  $\dot{J}_{\text{d}}$  is the angular momentum flux of the disk at  $r_{\text{al}}$  and  $v_{\text{d}}(r_{\text{al}}) \simeq v_{\text{K}}(r_{\text{al}})$  is the disk angular velocity at  $r_{\text{al}}$ . Defining a disk viscous time scale

$$t_{\text{d}} \equiv \frac{M_{\text{d}}}{\dot{M}} = \eta t_{\text{acc}}, \quad (38)$$

and from Eqs. (29), (1), and (19). we have

$$\begin{aligned} t_{\text{al3}} &\sim \left(\frac{a}{r_{\text{al}}}\right)^{1/2} \eta^{-1} t_{\text{d}} \\ &\simeq 0.60 q_{-1}^{3/4} \alpha^{1/2} \dot{m}_{-1}^{-1/2} M_8^{-0.61} x_4^{1/40} t_{\text{d}}, \end{aligned} \quad (39)$$

where  $x_4 = r_{\text{al}}/10^4 r_{\text{G}}$ .

However, for an accretion disk in AGNs, the viscous parameter  $\alpha$  is  $\ll 1$  and the case is more complex (Scheuer & Feiler 1996; Natarajan & Pringle 1998). The effect of the binary on the accretion disk is to force the rotation axis of the disk to precess and to align with the binary orbital plane and by Newtonian third-law the binary orbit realigns with the accretion disk due to the feedback effect. Both precession and alignment take place on the same time scale similar to the realignment of rotating SMBH due to the Bardeen-Peterson effect, i.e.

$$t_{\text{al3}} \sim \Omega_{\text{ap}}^{-1}, \quad (40)$$

where  $\Omega_{\text{ap}}$  is the precessing angular velocity at  $r_{\text{al}}$ . From (28), (29), (1), and (42), this gives

$$t_{\text{al3}} \sim 0.49 \alpha_{-1}^{29/10} q_{-1}^{3/4} \dot{m}_{-1}^{-3/10} M_8^{0.79} x_3^{53/40} t_{\text{d}}, \quad (41)$$

where  $x_3 = a/10^3 r_{\text{G}}$ . Eqs. (41) and (39) give a similar result that it takes about half of the disk viscous time to realign the binary orbit with the outer accretion disk and that  $t_{\text{al3}} \sim 10^7 - 10^8$  yr. As the interaction of binary-disk takes place at  $a > a_{\text{cr}}$ , Eq. (37) suggests that the binary orbital plane should become coplanar with the accretion disk before the separation  $a$  becomes  $\ll a_{\text{cr}}$ . Therefore, the spin axis of the rotating central SMBH should be vertical to the accretion disk when the secondary merges into the primary due to gravitation wave radiation.

From Eqs. (38), (3) and (4), we have

$$t_{\text{d}} = 2.2 \times 10^8 \text{ yr } \alpha_{-2}^{-4/5} \dot{m}_{-1}^{-2/5} M_8^{0.556}. \quad (42)$$

The lifetime of AGNs is a very important parameter in determining the fueling mechanism of AGNs and the SMBH growth. The most estimates of the net lifetime are in the range  $t_{\text{Q}} = 10^7 - 10^8$  yr for luminous Quasars with central SMBHs of mass  $M \sim 10^8 - 10^9 M_{\odot}$  (Haehnelt, Natarajan & Rees 1998; Martini & Weinberg 2001; Steidel *et al.* 2002; Yu & Tremaine 2002) and most probably  $t_{\text{Q}} \simeq 5 \times 10^7$  yr (Jakobsen *et al.* 2003) and  $t_{\text{Q}} \sim 6.6 \times 10^5$  yr for miniquasars with central SMBHs of mass  $M \sim 10^5 M_{\odot}$  (Haiman & Loeb 1998, 1999) (for recent review see Martini (2003)). It is generally believed that the accretions in luminous QSOs and in miniquasars are approximately at the Eddington rate. Taking

the fiducial value of the parameters,  $\alpha = 0.03$ ,  $\dot{m} = 1$  and  $M_8 = 1$  for luminous QSOs and  $M_8 \sim 10^{-3}$  for miniquasars, we have  $t_d = 3.6 \times 10^7$  yr for luminous QSOs and  $t_d = 7.8 \times 10^5$  yr for miniquasars which are consistent with the estimates in the literature. Therefore, we take the disk viscous time scale  $t_d$  as an indicator of the lifetimes of an accretion disk and of AGNs. Eq. (38) implies that SMBBHs in AGNs should merge within the viscous time scale of an accretion disk. While Eq. (41) suggests that binary orbital plane and the rotating central SMBH stays misaligned with the outer accretion disk with a random inclination angle with respect to the outer accretion disk for a great fraction of the viscous time of an accretion disk and of the life time of AGNs.

When the binary orbital orbit becomes coplanar with the accretion disk, the secondary black hole opens a gap in the accretion disk and exchanges angular momentum with outer disk gas via gravitational torques, leading to shrink of the binary separation on a viscous time scale  $t_{\text{acc}}$  (Lin & Papaloizou 1986; Ivanov *et al.* 1999; Armitage & Natarajan 2002). The interaction of SMBBHs and a coplanar accretion disk and the final coalescence of SMBBHs has been discussed in detail by Liu *et al.* (2003).

#### 4 JET ORIENTATION AND THE FORMATION OF X-SHAPED FEATURE IN RADIO GALAXIES

In Sec. 2 and Sec. 3, we discussed the possible SMBBHs-disk system and their interaction in a sub-parsec scale. As relativistic jets in radio sources most likely initiate forming before the two supermassive black holes become bound, the relativistic jets may have developed to a large-scale size when the binary becomes hard and interact with accretion disk. It is believed that relativistic plasma jets form along the spin axis of central SMBH and are perpendicular to the accretion disk due to Bardeen-Peterson effect (Rees 1984; Marscher *et al.* 2002),

When the orbital radius of binary is less than the radius  $a_m$  and the accretion disk is still a standard  $\alpha$ -disk with accretion rate  $\dot{m} > \dot{m}_{\text{cr}} \sim 10^{-2} - 10^{-1}$ , the secondary realigns the central rotating SMBH via binary-disk interaction, leading to reorientations of its spin axis and of the relativistic jets with a reorientation time scale  $t_{\text{all}} \lesssim 10^5$  yr. As a relic radio lobe can be detected within about  $t_{\text{relic}} \sim 10^6 - 10^8$  yr depending on the environment (Komissarov & Gubanov 1994; Slee *et al.* 2001; Kaiser & Cotter 2002), the reorientation of radio jets may be observed in some radio sources. Actually, the observed X-shaped (or



winged) radio sources (Leahy & Parma 1992; Dennett-Thorpe *et al.* 2002) might be such objects.

#### 4.1 Summary of observations of X-shaped radio sources

X-shaped, or winged, radio galaxies (Högbom & Carlsson 1974) are a subclass of extragalactic radio sources of very peculiar morphology: a second axis of symmetry of two large-scale old diffuse wings or tails, orienting at an angle to the currently active lobes (Dennett-Thorpe *et al.* 2002; Capetti *et al.* 2002). Many observations have been done to these sources and show that (1) the winged sources are about 7 per cent of the sample radio galaxies investigated by Leahy & Parma (1992) and (2) they are low-luminous FRII or borderline FRI/FRII radio galaxies and none of them belongs to FRI-type (Dennett-Thorpe *et al.* 2002); (3) there is no evidence for a merger with a large galaxy in the last  $\sim 10^8$  yr (Dennett-Thorpe *et al.* 2002) in the sources except B2 0828+32 (Ulrich & Roennback 1996) and 3C 293 (Evans *et al.* 1999; Martel *et al.* 1999); (4) all are narrow-line galaxies except 4C +01.30 which show weak broad emission lines (Wang *et al.* 2003); (5) the old wings as long as, or even longer than, the directly powered active lobes have no pronounced spectral gradients and form due to a jet reorientation within a few Myr (Dennett-Thorpe *et al.* 2002); (6) the wings are aligned with the minor axis and vertical to the major axis of the host galaxy (Capetti *et al.* 2002; Wang *et al.* 2003); (7) the active radio lobes have a random inclination angle relative to the major axis of host galaxy; (8) the host galaxy has a high eccentricity (Capetti *et al.* 2002); and (9) the wings are Z-symmetric (Gopal-Krishna *et al.* 2003).

#### 4.2 Models in literature and their difficulties

Several scenarios have been suggested for the formation of the X-shaped structure in some FRII radio sources in literature: (1) back-flow of radio plasma from the active lobes into wings via buoyancy (Leahy & Williams 1984) or diversion through the galactic disk (Capetti *et al.* 2002); (2) slow conical precession of jet axis (Parma *et al.* 1985); (3) quick reorientation of jet axis with or without turnoff of jet formation for some time (Dennett-Thorpe *et al.* 2002; Merritt & Ekers 2002). Dennett-Thorpe *et al.* (2002) review all the models and find that the first two are inconsistent with the observations and the third scenario together minor galaxy mergers is favored.

A rapid reorientation of jet axis may result from the realignment of a rotating SMBHs due to Bardeen-Petsrean effect with a misaligned accretion disk which forms due to the disk instabilities (Dennett-Thorpe *et al.* 2002), or from the spin-flip of the active SMBH due to the coalescence of an inclined binary black holes (Dennett-Thorpe *et al.* 2002; Merritt & Ekers 2002; Zier & Biermann 2001). However, disk instabilities would be suppressed even by a mild rotation of the SMBH and cannot explain the straightness of jet from VLBI- to VLA-scale (Pringle 1996). Another difficulty with the disk instability model is in explaining why such instability does not exist in other radio galaxies which have stable jet direction and why it occurred only once in the X-shaped sources (Dennett-Thorpe *et al.* 2002).

Merritt & Ekers (2002) suggest that the rapid change of jet orientation may be due to a spin-flip of the central active black hole due to a coalescence of misaligned SMBBHs. To explain the detection rate of X-shaped radio sources, they show that the merger has to be minor. Although the observations of X-shaped radio sources favor minor merger scenario (Dennett-Thorpe *et al.* 2002; Gopal-Krishna *et al.* 2003), the spin-flip picture has several defects. First of all, inclined rotating SMBH formed via the binary coalescence should realign with the accretion disk due to the Bardeen-Peterson effect on a short time scale  $t_{\text{al1}} \lesssim 10^5$  yr, implying that the relativistic jets reorients in the direction of the old wings on the time scale and we should detect a distorted jet of a length  $l_j \sim t_{\text{al1}} v_j \lesssim 10$  kpc for a typical jet velocity  $v_j \sim 0.3c$  instead of straight wings of hundreds Kpc. Secondly, Merritt & Ekers do the calculation with Newtonian approximation, while calculations basing on general relativity show that the change in inclination of a rotating central SMBH is negligible in a minor merger and a significant reorientation of the active SMBH requires a comparatively rare major merger (Hughes & Blandford 2003). Thirdly, as we show in Sec. 3 that binary-disk interactions would align a central SMBH with an inclined binary orbital plane before the binary coalesces and that no change in the orientation of spin axis of the central SMBH happens even in a major merger. The last is from the observations. The model does not reasonably explain the sharp transition that X-shaped feature is detected only in FR II radio galaxies but not in FR I radio galaxy with similar luminosity.

### 4.3 Reorientation of radio jets in FR II radio galaxies

Here we suggest that the formation of X-shaped feature in some radio sources is due to the realignment of the rotating central SMBHs with the binary orbital plane via binary-disk

interaction and the Bardeen-Peterson effect. In this scenario, the accretion disk and the gas in galactic disk have already settled down and large scale relativistic jets in radio galaxies have formed, before the secondary SMBH distorts the accretion disk. It is expected that the accretion disk is nearly coplanar with the dust lane or galactic disk due to the conservation of angular momentum of gas. Thus, the large scale relativistic radio jets and lobes are nearly vertical to the galactic plane.

If the accretion rate is greater than the critical rate  $\dot{m}_{\text{cr}} \sim 10^{-2} - 10^{-1}$  and the accretion disk is a standard thin-disk, the twisted disk reorients the spin axis of the rotating SMBH, leading to the rapid change of jet direction on a time scale  $t_{\text{reor}} \sim t_{\text{al1}} \lesssim 10^5$  yr. The relic of the old radio lobes forms the detected old wings in the X-shaped radio sources. As the jet before the reorientation is vertical to the accretion disk, the wings are expected to be nearly perpendicular to the galactic plane, as is observed.

The winged radio source 4C +01.30 shows weak broad emission lines and contains a partially obscured quasar nucleus. The mass of its central SMBH is  $M \sim 4 \times 10^8 M_{\odot}$  and the accretion disk is a standard  $\alpha$ -disk with  $\dot{m} = L/L_{\text{Edd}} \simeq 0.2$  (Wang *et al.* 2003). From Eq. (9), the reorientation takes place on a time scale  $t_{\text{reor}} \simeq 2 \times 10^5$  yr for typical parameters  $a_* = 0.7$ ,  $\alpha = 0.03$  and  $\epsilon = 0.3$ . From Eq. (25), the disk becomes twisted and warped due to the interaction with the secondary and coplanar with the binary orbital plane on a time scale  $t_{\text{al2}} \simeq 4 \times 10^4$  yr. From Eq. (42), the viscous time of the sources is  $t_{\text{life}} \simeq 1.5 \times 10^8$  yr. The mass ratio of accretion disk and the secondary SMBH is  $\eta \approx 7q_{-1}^{-1}$  and  $\eta > 1$  even for a major merger with  $q \sim 0.7$ .

As the other X-shaped radio galaxies show only narrow emission lines, the central quasar nuclei may have been completely obscured by the dust torus and the X-shaped sources are edge-on. It is easy to be understood as observations prefer to detecting X-shaped feature in radio sources with large scale projected jets. Therefore, the high eccentricity of the host galaxy of X-shaped radio sources is most likely due to selection effects and does not relate to the origin of the X-shaped structure. This might be the reason why in the control sample of radio galaxies used by Capetti *et al.* (2002) the radio galaxies with host galaxy of a similar or even higher eccentricity do not show winged feature.

#### 4.4 The missing of winged FRI radio galaxies

It is possible that the accretion rate has become less than the critical rate  $\dot{m}_{\text{cr}}$  and accretion disk is no longer a standard  $\alpha$ -disk but a radiatively inefficient accretion flow, e.g. an ADAF, when the interaction between the secondary and an accretion disk starts. As the interaction between an ADAF and a binary is negligible, reorientation of the spin axis of the central SMBH takes place on a very long time scale  $t_{\text{hd}} \sim 10^9$  yr which is longer than the observable time scale of a radio relic  $t_{\text{relic}} \sim 10^7 - 10^8$  yr (see the discussion below). As the transition of FRI and FRII radio galaxies is related to an accretion rate  $\dot{m}_{\text{FR}} \sim \dot{m}_{\text{cr}}$  (Ghisellini & Celotti 2001; Cavaliere & D’Elia 2002; Maraschi & Tavecchio 2003), the FR division may reflect the transition of accretion mode from a standard disk to a radiatively inefficient accretion flow and the accretion disk in FRI radio galaxies is radiatively inefficient. This implies that the binary-disk interaction cannot form a winged structure in FRI radio sources and the missing of X-shaped FRI radio sources is due to the radiatively inefficient accretion mode, i.e. ADAF, ADIO, or CADF. However, it is possible that the outer part of accretion disk is standard and the inner accretion flow is an ADAF. In this case, the interaction between the binary and the outer accretion disk can twist the part of standard disk on a time scale  $t_{\text{al2}} \sim 10^3$  yr but the inner ADAF realign the central rotating black hole on a time scale  $t_{\text{al1}} \sim 10^7$  yr for  $\alpha_{\text{AD}} \sim 0.15$  and  $\dot{m} \sim 10^{-2}$  which is on the same order of the relic time  $t_{\text{relic}}$ . Here, we use Eq. (9) to estimate the realignment time scale for a transition system  $\dot{m}\dot{m}_{\text{cr}}$ . Therefore, it is expected that S-shaped structure would be observed in high-luminous FRI radio sources.

One possibility to detect X-shaped feature in FRI radio sources is that radio sources evolves from FRII type into FRI type after the wings forms with  $t_{\text{al3}} > t_{\text{d}}$ . From Eqs. (41), this implies

$$q > 1.5 \left( \frac{\alpha}{0.05} \right)^{-58/15} \dot{m}_{-2}^{2/5} M_8^{-1.05} x_3^{-53/30}. \quad (43)$$

As the mass ratio  $q$  should be smaller than unit, Eq. (43) implies that no X-shaped FRI radio galaxy is possible to form.

#### 4.5 Evidence against recent mergers

The undisturbed properties of host galaxies of winged radio sources except 3C293 imply that mergers are minor or, if major, longer than a few  $10^8$  yr ago. Eq. (12) shows that two SMBHs become bound on a time scale  $\sim 10^8$  yr. A bound binary becomes hard and interacts

with an accretion disk at a pc-scale on a similar time scale (cf Yu (2002)). Therefore, the galaxy merging in X-shaped radio sources may occur  $\sim 10^9$  yr ago in our scenario which is consistent with the observations of 3C 293 (Evans *et al.* 1999).

3C293 is the only winged source showing obvious signs of interaction of a tidal tail and a close companion galaxy (Evans *et al.* 1999; Martel *et al.* 1999). The relative masses of its host galaxy and the companion suggest that the tidal feature is most likely a remnant from a merger event occurring more than  $t_{\text{td}} \sim 10^9$  yr ago (Evans *et al.* 1999). The spectroscopy observations of central bulge region show strong CO emission line with a velocity width  $\sim 400 \text{ km s}^{-1}$ . From Eq. (11), the mass of the central SMBH is  $M \simeq 2.2 \times 10^9 M_{\odot}$ . If we take  $t_{\text{td}} \sim 10^9 \text{ yr} \sim 2t_{\text{bd}}$ , Eq. (12) gives a mass ratio  $q \sim 0.3$ , implying that the merger in 3C293 is minor but with a moderate mass ratio and is rare. This is consistent the observations that the merger occurred quite long time ago but still can be detected and that 3C293 is the only X-shaped radio source showing signs of interaction. The mass ratio of the disk and the secondary is  $\eta \sim 9\alpha_{-2}^{-4/5} \dot{m}_{-1}^{3/5}$  and  $\eta > 1$  for  $\dot{m} > \dot{m}_{\text{cr}}$ . Therefore, the binary black hole will become realigned with the outer accretion disk and merger into one more massive SMBH, leading to the formation of a double-double FRII radio galaxy. From Eq. (24), the interaction happens likely at  $\lesssim 3.6 \times 10^2 r_{\text{G}} \alpha_{-2}^{4/7} \dot{m}_{-1}^{-3/7} \sim 0.08 \text{ pc}$ , which is much less than the disk size  $r_{\text{d}} \simeq 0.4 \text{ pc}$ .

#### 4.6 Detection rate of winged radio sources and the lifetime of low luminosity FRII radio galaxies

Leahy & Parma (1992) show that the probability  $\lambda_{\text{X}}$  of detecting a FRII radio source with X-shaped radio feature is  $\approx 7\%$  in a sample of radio galaxies with luminosity between  $3 \times 10^{24}$  and  $3 \times 10^{26} \text{ W Hz}^{-1}$  at 1.4 GHz. The detection rate depends both on the mean observable time scale,  $t_{\text{relic}}$ , of relic radio lobes and the minimum  $t_{\text{min}}$  between the life time  $t_{\text{life}}$  of FRII radio galaxies and the mean detectable time  $t_{\text{merger}}$  between mergers,  $t_{\text{min}} = \min(t_{\text{life}}, t_{\text{merger}})$ . It is difficult to accurately estimate the mean timescale  $t_{\text{relic}}$  in a survey sample. The estimated time scale  $t_{\text{relic}}$  is in the range of  $\sim 10^6 - 10^8$  yr, depending on both the environment and the survey frequency (Komissarov & Gubanov 1994; Slee *et al.* 2001; Kaiser & Cotter 2002), which is consistent with the spectrally estimated age limit of radio wings in some X-shaped sources:  $< 34 \text{ Myr}$  for 3C223.1 and  $< 17 \text{ Myr}$  for 3C403 (Dennett-Thorpe *et al.* 2002), and  $< 75 \text{ Myr}$  for B2 0828+32 (Klein *et al.* 1995).

From the measured rate and the timescale  $t_{\text{relic}}$ , we have

$$t_{\text{min}} = \frac{t_{\text{relic}}}{\lambda_X} \lesssim 10^9 \text{ yr} \left( \frac{t_{\text{relic}}}{10^8 \text{ yr}} \right). \quad (44)$$

Merritt & Ekers (2002) take the upper limit  $t_{\text{relic}} \sim 10^8 \text{ yr}$  and get  $t_{\text{min}} \simeq 10^9 \text{ yr}$ , which is too large to be the age of radio sources. They interpret  $t_{\text{min}}$  as the mean merge time scale of galaxy,  $t_{\text{merge}}$ , which is higher than the estimate of the galaxy merge rate given in literature (Haehnelt 1998; Carlberg *et al.* 2000) although it is not implausible. However, a relic with an age  $t_{\text{relic}} \sim 10^8 \text{ yr}$  is most likely invisible even at a very low survey frequency due to expansion and radiation. To use the detection rate given by Leahy & Parma (1992) for a sample of low luminous FR II radio galaxies with a high survey frequency 1.4 GHz, it is most plausible to adopt  $t_{\text{relic}} \approx 10^7 \text{ yr}$ , which gives  $t_{\text{min}} \simeq 10^8 \text{ yr}$ . As the life time  $t_{\text{life}}$  of low luminosity FR II radio galaxies is much less than the mean merge time scale  $t_{\text{merge}}$  of galaxy which is  $\gtrsim 10^9 \text{ yr}$ , we take  $t_{\text{min}}$  as the mean lifetime of low luminous FR II radio sources and have  $t_{\text{life}} \sim 10^8 \text{ yr}$ , which is consistent with the estimated lifetime  $t_{\text{life}} \sim 10^8 \text{ yr}$  for low-luminous AGNs in literature. As in low luminous FR II radio galaxies the accretion rate is  $\dot{m} \gtrsim \dot{m}_{\text{FR}}$ , we take a mean accretion rate  $\dot{m} \sim 0.1$  for the Leahy & Parma's sample and from Eq. (42) obtain a disk viscous time  $t_d \simeq 10^8 \text{ yr}$  for  $\alpha = 0.03$ . The estimates of the lifetime of low luminous FR II radio sources in different ways are consistent with each other very well.

#### 4.7 Orientations of wings and active radio lobes in FR II radio sources

As an accretion disk forms with gas of low angular momentum in a merging system of galaxies and the gas is settled down into the galactic plane with low gravitational potential. It is expected that large-scale relativistic plasma jets are perpendicular to accretion disk due to the Bardeen-Peterson effect and to the galactic plane. Since the radio wings in X-shaped radio sources are the relics of radio jets and lobes, they should be vertical to the major axis of host galaxy. While the orientations of active jets are aligned with the rotation axis of binary and distribute randomly. This is consistent with the observations of X-shaped radio galaxies (Capetti *et al.* 2002) that the wings in all the winged radio galaxies are nearly aligned with the minor axis of host galaxy and the active lobes have no preferential orientation.

To reorient the rotating central SMBH, the accretion disk has to be standard with  $\dot{m} > \dot{m}_{\text{cr}}$  and thus the radio galaxies morphologically belong to FR II-type. However, if binary hardening time scale ( $\sim t_{\text{bd}}$ ) is much larger than the disk viscous time  $t_d$ , the accretion disk

becomes an radiatively inefficient disk, e.g. ADAF, with  $\dot{m} < \dot{m}_{\text{cr}} \sim \dot{m}_{\text{FR}}$  before binary-disk interaction. Thus, a radio source evolves from FRII- into FRI- class without the formation of X-shaped radio structure. Eqs. (12) and (42) suggest that X-shaped radio structure cannot form in a galaxy merging with a mass ratio

$$q \ll q_X \equiv 3 \times 10^{-2} M_8^{-0.08} \alpha_{-2}^{1.07} \dot{m}_{-2}^{0.54}. \quad (45)$$

Therefore, the mass ratio in any X-shaped FRII radio galaxies should be  $q \gtrsim 10^{-2}$ , which is consistent with the estimates of the X-shaped sources 3C293 and 4C+01.30. From Eqs. (26) and (45), we have  $J_b \gg J_{\text{BH}}$  even for a central SMBH with  $a_* \sim 1$ . Eqs. (13) and (45) imply that nearly all of the hard binary systems formed during galaxy merging within Hubble time would produce X-shaped feature.

When a binary twists inner accretion disk and aligns the central SMBH, the orbital plane stays inclined for a time scale  $t_{\text{al3}}$  which is a great large fraction of the disk viscous time  $t_d$ . It is expected that large scale jets in most of FRII radio sources would randomly orients with respect to the major axis of host galaxy. The inclined radio jets in radio galaxies are nearly aligned from the VLBI to the VLA as  $t_{\text{al3}} \sim 10^7 - 10^8 \text{ yr} > t_{\text{relic}} \gtrsim 10^7 \text{ yr}$ . When the binary orbital plane becomes coplanar with the outer accretion disk, radio jet becomes vertical to the galactic plane and aligned with the minor axis of host galaxy. After the binary becomes coplanar with outer accretion disk, they merge on a short time scale and the radio source becomes a DDRG (Liu *et al.* 2003). Therefore, the fraction of FRII radio galaxies with vertical large scale radio jets is small. When a radio source becomes a DDRG, the mass in the inner accretion disk has been removed, accelerating the evolution of the disk. It is expected that the accretion disk becomes radiatively inefficient on relatively short time  $< t_d$ . Therefore, the fraction of FRII radio galaxies with random orientation of jet is determined by the ratio  $t_{\text{al3}}/t_{\text{acc}} \sim 1$ .

The random orientations of jets in FRII radio galaxies may have been observed. It is found that the jet orientations in radio sources randomly distribute relative to the dust lane or the major axis of host galaxy (Birkinshaw & Davies 1985; Schmitt *et al.* 2002). There is no significant correlations between the misalignment angle and any of the intrinsic kinematic parameters of host galaxy, in particular rotation velocity and central velocity dispersion which is related to the mass of central SMBH. Schmitt *et al.* (2002) show that the dust disks are closely aligned with the major axis of host galaxy and the jets are well aligned from the VLBI to the VLA scales. None of the possible mechanisms for the origin of the

observed misalignment between jet and the rotation axis of host galaxy could consistently explain the observations (Schmitt *et al.* 2002). In our scenario, jet orientation is determined by the impact angle of the merging galaxy and the misaligned angle between radio jet and the minor axis in FR II radio galaxies should be independent of any intrinsic kinematic parameter of the parent galaxy. However, the model suggests that the misalignment occurs in an accretion disk at pc scale inside the broad line region (BLR). As the emission line flux depends on the ionization radiation which is a function of the inclination angle between the inner radiation region and BLR and the BLR cover factor. A positive correlation between the misalignment angle and the relative line flux may be expected.

Two more important implications of the model are that the distribution of jet orientation depends on the FR type and that the jets in DDRGs are nearly vertical to the major axis of host galaxy. We will discuss the two predications in more detail in Sec. 4.8 and Sec. 5.

#### 4.8 Relationship of FRI and FR II radio sources and jet orientations in FRI radio sources

As all young AGNs have been detected as FR II radio galaxies, it is most likely that FRI radio sources is evolved from FR II-type (O’Dea 1998). There are three possible ways for a radio source to evolve from FR II- to FRI-type in our scenario. If the activity of a FRI radio source is triggered by minor mergers with mass ratio  $q \ll q_X$ , the evolution finishes before the binary-disk interaction. In those sources (Class I FRI radio sources), the change of jet orientation due to the interaction may occur on a time scale  $t_{\text{al1}} \sim 10^7 - 10^8$  yr, leading to the formation of S-shaped structure in FRI radio sources. As the realignment time scale  $t_{\text{al1}}$  inversely correlates with the accretion rate  $\dot{m}$ , S-shaped radio structure are most likely to form in luminous FRI radio sources with accretion rate close to  $\dot{m}_{\text{FR}} \sim \dot{m}_{\text{cr}}$ . The jet orientations in most the Class I FRI radio sources are random relative to the galactic plane of host galaxy. Since Class I FRI radio sources should contain binary of mass ratio  $q_{\text{cr}} \sim 5 \times 10^{-4} \ll q \ll q_X \sim 10^{-2}$ , they should make up  $\lesssim 1/5$  of FRI radio sources. Class FRI radio galaxies have linear size larger than their progenitor FR II radio galaxies do.

While most radio sources with larger mass ratio  $q \gtrsim q_X$  spend much more time on FR II phase, which have more energetic radio jets with larger size. The second possible case is that the alignment time scale  $t_{\text{al3}}$  in a FR II radio source is much larger than the disk viscous time scale  $t_{\text{d}}$  and the accretion disk becomes radiatively inefficient before the outer disk-binary



realignment. The jets in these subclass FRI radio sources (Class II) randomly orient. ClassII FRI radio sources have an average linear size larger than that of ClassI FRI radio galaxies. From Eq. (41), the activity of ClassII FRI radio sources must be triggered by major mergers with  $q \gg 0.1$ . Therefore, the ClassII FRI radio galaxies with random jet orientation and largest size make up a very small fraction of FRI radio sources as major mergers in galaxy merging is very rare.

Most radio sources evolve from FRII- into FRI-type after the binary plane becomes coplanar with outer accretion disk and the galactic plane. Liu *et al.* (2003) and the discussion in Secs. 4.7 and 5 show that SMBBHs become merged on a time scale  $\lesssim t_{\text{acc}}$  and FRII radio galaxies become DDRGs, before evolving from FRII- to FRI-type. Radio jets in this subclass of FRI radio sources (Class III) should be vertical to the galactic plane and aligned with the minor axis of host galaxy. After the galaxies become DDRGs and the radio jets restart, the accretion rate becomes  $1 \gg \dot{m} \gtrsim \dot{m}_{\text{cr}} \sim \dot{m}_{\text{FR}}$ . The re-born radio sources have FRII morphology with jet less powerful than that in normal FRII radio galaxies. Since the formation of jet is interrupted for quite long time before the radio sources evolves from FRII- to FRI-types, the size of active radio lobes in ClassIII FRI radio sources is the size of the re-born sources and as large as that of the ClassI FRI radio sources which is much smaller than the size of most FRII radio galaxies. Therefore, our conclusion is that the average linear size of FRI radio galaxies is smaller than that of FRII radio galaxies. However, the relics of up to four giant radio lobes could be detected in some ClassIII FRI radio galaxies as the sources become giant when they become DDRGs (Liu *et al.* 2003).

The two predications about jet orientations and source size of radio sources can be tested. We note that de Koff *et al.* (2000) suggests that the jet orientations in FRII radio galaxies randomly distributes while the jets in most FRI radio sources are vertical to the major axis of host galaxy. However, the conclusion is based on a small sample of radio galaxies and should be checked with much larger sample of radio sources.

## 5 RELATIONSHIP BETWEEN X-SHAPED AND DOUBLE-DOUBLE RADIO GALAXIES

In a minor mergers of mass ratio  $q \gtrsim q_X$ , the binary orbital plane and the accretion disk becomes coplanar on a time scale  $t_{\text{al3}} \sim 10^7 - 10^8$  yr after an X-shaped radio structure forms in a FRII radio galaxy. The secondary SMBH opens a gap in the accretion disk and ex-

changes angular momentum with disc gas via gravitational torques for a minor merger with  $q > q_{\min} = (81\pi/8)\alpha\delta^2 \simeq 3 \times 10^{-5}\alpha_{-2}\delta_{-2}^2$  (Lin & Papaloizou 1986). The secondary migrates inwards on a viscous timescale  $\sim t_{\text{acc}}$  and merges into the primary, leading to the removal of the inner accretion disk and to an interruption of jet formation (Liu *et al.* 2003). Liu *et al.* (2003) identify DDRGs (Schoenmakers *et al.* 2000) with the objects in which coalescence of SMBBHs, removal of inner accretion disk and interruption of jet formation occurred. DDRGs are a subclass of giant FRII radio galaxies, consisting of a pair of symmetric double-lobed structures with one common center. The new-born inner structure with relative low luminosity is well aligned with the outer old lobes. The generation of inner lobes in DDRGs is due to the interaction of warm clouds and recurrent jets of interruption time  $\sim \text{My}$  (Kaiser *et al.* 2000; Schoenmakers *et al.* 2000). When interruption time is  $\ll 10^6 \text{yr}$ , the interaction of the recurrent jet and intergalactic medium could not produce new lobes (Kaiser *et al.* 2000), as may be the case in the non-DDRG recurrent sources 3C288 (Bridle *et al.* 1989), 3C219 (Clarke *et al.* 1992), and B1144+352 (Schoenmakers *et al.* 1999).

The scenario of the binary coalescence and disk removal (Liu *et al.* 2003) implies that nearly all the SMBBHs in FRII radio galaxies merge into one more massive black hole and that all the winged radio sources would evolve into double-double radio galaxies on a time scale  $t_{\text{X-DD}} \sim t_{\text{acc}}$ . This picture is consistent with that double-double lobes are detected only in FRII radio galaxies. As the outer accretion disk is nearly aligned with the outer galactic plane, it is expected that the restarting jets in DDRGs is vertical to the major axis of host galaxy and aligned with the old radio wings in its X-shaped progenitor. We are statistically testing this predication and our preliminary results confirm the predication that the jets in DDRGs are well aligned with the minor axis of host galaxy (Liu *et al.* 2003a).

As the active jets in DDRGs is aligned with the old wings and  $t_{\text{X-DD}} \sim 10^7 - 10^8 \text{yr} \gtrsim t_{\text{relic}}$ , it is impossible to detect the co-existence of the wings and the double-double lobes in one DDRG. However, it is possible to detect the coexistence of double-double radio lobes and the cavities in the IGM, excavated by the past plasma jet with randomly orientation and filled with back-flow radio plasma from the outer double lobes. The cavities formed in such a way should have straight and sharp edges toward the core on the opposite side and diffusive edges on the same side of the active radio jets. The observations of the FRII radio galaxy J0116-473 may fit the description. Saripalli *et al.* (2002) show that J0116-473 is a low-luminosity FRII radio galaxy and contains both double-double radio lobes and a bar-like feature with sharply bounded northern edge. The observations show that the bar-like

feature may have an age of  $\sim 10^8$  yr and the present activity restarts about  $\sim (3-4) \times 10^6$  yr ago. The elapsed time since the last energy supply to the outer giant lobes is smaller than  $< 7 \times 10^7$  yr (Saripalli *et al.* 2002). If J0116-473 contained SMBBHs once before and the bar-like structure is the cavity produced by the past misaligned jet and filled with the back-flow plasma due to the alignment of the binary orbital plane with outer accretion disk on a time scale  $t_{\text{al3}} \sim t_{\text{acc}}$ . The estimated age  $t_{\text{acc}} \sim 10^8$  yr, of the bar-like feature together with Eq. (23) implies that the mass ratio  $q \simeq 0.2\dot{m}_{-1}$  and the merger is minor with  $q > q_X$ .

Since DDRGs evolve from X-shaped radio galaxies, it is expected that double-double radio lobes like X-shaped feature should be detected only in FR II radio sources. The probability  $\lambda_{\text{DD}}$  to detect recurrent jets in FR II radio sources is  $\lambda_{\text{DD}} \sim t_{\text{DD}}/t_{\text{life}}$ , where  $t_{\text{DD}} = t_{\text{int}} + t_{\text{tr}}$  with  $t_{\text{int}}$  the interruption time scale of jet formation and  $t_{\text{tr}} = l_j/v_{\text{lobe}}$  is the time scale for relativistic plasma lobes to travel along jet from central engine to outer relic radio lobes. For a typical value of advancing velocity  $v_{\text{lobe}} \sim 0.2c$  and a typical length scale of giant radio sources  $l_j \sim 1$  Mpc, we have  $t_{\text{tr}} \sim 10^7$  yr. As the interruption time scale  $t_{\text{int}} \sim \text{Myr}$ , we adopt  $t_{\text{DD}} \simeq 10^7$  yr and obtain  $\lambda_{\text{DD}} \lesssim 5$  per cent. From Eq. (44), we have

$$\lambda_{\text{DD}} = \left( \frac{t_{\text{DD}}}{t_{\text{relic}}} \right) \lambda_X < \lambda_X \quad (46)$$

with  $t_{\text{DD}} < T_{\text{relic}}$ . Eq. (46) suggests that the detection rate of DDRGs in a sample of FR II radio sources is between  $(1-10)\%$ . In estimating the time scale  $t_{\text{tr}}$ , we used the length scale of giant radio sources as Liu *et al.* (2003) suggest that the radio galaxies would become giant when they become DDRGs. As the accretion rate to produce the restarting relativistic jets is much smaller than the one producing the relic outer lobes, the active jets in DDRGs are much less luminous and may not be able to reach the outer lobes on the time scale  $\sim t_{\text{relic}}$ . If so,  $t_{\text{tr}} \sim t_{\text{relic}}$  and  $\lambda_{\text{DD}} \simeq \lambda_X$ . If the giant radio galaxies form mainly due to the explosive increase of accretion rate via the interaction of SMBBHs and accretion disk, the detection rate of recurrent jets in a sample of giant radio galaxies may be as high as  $\sim 100\%$ .

## 6 DISCUSSIONS AND CONCLUSIONS

Galactic dynamical simulations show that SMBBHs may stall, when it becomes hard at  $a_h \sim 0.01 - 1$  pc, and merge on a timescale may longer than Hubble time. We show that the interaction of accretion disk and SMBBHs may dominate the evolution of a binary formed during galaxy merging within Hubble time, after it becomes hard. We investigate the interaction of inclined SMBBHs and an accretion disk at sub-parsec scale and its feasibility

to significantly change the orientation of the spin axis of central SMBH, which is believed to be aligned with the orientation of relativistic jets in AGNs. We identify the interaction and the reorientations of spin axis of central black hole with jet orientations in some radio sources.

It is shown that the inclined secondary twists the accretion disk and aligns the inner accretion disk. We analytically calculate the alignment time scale and show that the alignment finishes on a time scale  $\sim 10^3$  yr which is the same result as the one obtained with numerical computations by Ivanov *et al.* (1999) who also numerically calculate the alignment. We show that the quick alignment of the inner accretion disk is slowed down at the Bardeen-Peterson radius  $r_{\text{BP}} \sim 20r_{\text{G}}$  and completed on an another timescale  $t_{\text{all}} \sim 10^4$  yr due to the Bardeen-Peterson effect, which is associated with the reorientation timescale of relativistic plasma jets. We suggest that the reorientation of spin axis of central rotating SMBH causes the formation of X-shaped feature observed in some FRII radio galaxies. In our scenario, the wing of X-shaped radio sources is the relic of past jets and lobes and its alignment with the minor axis of host galaxy is due to the conservation of angular momentum of accreting gas and the alignment of the accretion disk and the galactic plane. The random distribution of orientation of active jet is due to the random impact of two merging galaxies. The back-flow-diversion model (Capetti *et al.* 2002) suggests that a back-flow is driven out along the minor axis of host galaxy due to the largest pressure gradient in the direction. However, the picture cannot explain why many radio galaxies with similar luminosity and eccentricity of host galaxy have no X-shaped feature and why the size of wings in some X-shaped radio sources are much larger than the directly powered lobes. Although the spin-flip model has theoretical problem if a merger is minor, it is possible to have old wings along the minor of host galaxy if the merger is major and the coalescence of two black holes finishes on a time scale  $\ll t_{\text{all}} \sim 10^4$  yr. The difficulty with the scenario is that the new-born jet is distorted due to the Bardeen-Peterson effect and becomes realigned with the old wings on a time scale  $\lesssim 10^5$  yr, which implies a distorted jet of size  $\lesssim 10$  Kpc instead of a straight large scale radio jets.

To be more specification, we consistently explain the observations of X-shaped radio galaxies with our scenario and in particularly apply it to the two winged sources 4C+01.30 and 3C293. We show that the mass ratio of the secondary and the primary in the 4C+01.30 and 3C293 are indeed minor with  $q \sim 0.2$  and the reorientation happens on time  $\sim 2 \times 10^5$  yr which is consistent with the observation of  $\lesssim$  Myr.

Basing the model and the detection rate  $\sim 7\%$  of X-shaped structure in a low luminous FR II radio galaxies (Leahy & Parma 1992), we estimate the average lifetime of low luminous FR II radio sources to be  $t_{\text{life}} \sim 10^8$  yr if taking a mean observable timescale,  $t_{\text{relic}} \sim 10^7$  yr, of the relic of radio lobes in Leahy & Parma's sample. The estimate of the lifetime of low luminous FR II radio sources is consistent with the estimates of low luminous AGNs and the disk viscous time scale but much larger than the estimate for QSOs which may accrete at the Eddington accretion rate. This is reasonable if the activity of AGNs is triggered by a the minor merger. The theoretical calculation also shows that the interaction of accretion disk and a binary formed by a minor merger can lead to the formation of X-shaped structure in radio galaxies. In the back-flow model, wings form by the back-flow plasma in each radio galaxies with high eccentricity (Capetti *et al.* 2002), which suggests the observation of X-shaped structure in each radio galaxy with similar eccentricity of host galaxy and is inconsistent with the observations. Merritt & Ekers (2002) take  $t_{\text{relic}} \simeq 10^8$  yr in the spin-flip model and obtain  $t_{\text{life}} \sim 10^9$  yr. They suggest that the time scale  $t_{\text{life}}$  is the mean merger time scale of galaxy and obtain a coalescence rate of SMBBHs  $\sim 1 \text{ Gyr}^{-1}$  which is consistent with those inferred for galaxies in dense regions or groups but higher than most estimates of the overall galaxy merger rate (Haehnelt 1998; Carlberg *et al.* 2000). However, the explanation has two difficulties. The first of is that the relic of radio lobes cannot be detectable, especially at a survey frequency as high as 1.4GHz, on a time scale  $t_{\text{relic}} \sim 10^8$  yr due to radiation loss and plasma expansion. The other is that the mean life time of radio sources is much shorter than the mean merger timescale and the estimate  $t_{\text{life}}$  should be the average lifetime of radio sources with low luminosity between  $3 \times 10^{24} \text{ W Hz}^{-1}$  and  $3 \times 10^{26} \text{ W Hz}^{-1}$  at 1.4GHz.

In our model, the lack of X-shaped FRI radio galaxies may be due to the fact that the accretion flow in FRI radio galaxies is geometrically thick and optically thin and weakly interacts with SMBBHs. Or it may also be due to that FRI radio galaxies are evolved from FR II radio galaxies on a time scale much longer than the detectable time scale of relic lobes  $t_{\text{relic}}$ . As the accretion disk in FR II is standard with high accretion rate  $\dot{m} > \dot{m}_{\text{cr}}$  while radiatively inefficient accretion flow with accretion rate  $\dot{m} < \dot{m}_{\text{cr}}$ , it is most likely that radio galaxies evolves from FR II- to FRI-type. We discussed the three kinds of possible evolutions and suggest that the orientation of jet in most but not all FR II radio galaxies distributes randomly while is nearly vertical to galactic plane in most but not all FRI radio galaxies. The different distribution of jet orientation in different FR-type radio galaxies may be observed (de Koff *et al.* 2000). Schmitt *et al.* (2002) discussed all

the possible explanations in literature to the detected distribution of jet orientation and concluded that none of them is plausible. Here we give a reasonable model. However, the sample is too small to be very meaningful and the result needs to be confirmed with larger samples of radio galaxies.

Our model also suggests that all SMBBHs in FR II radio galaxies become coplanar with galactic plane and merge into a more massive black hole within the life time of the FR II radio galaxies. Liu *et al.* (2003) suggest that the coalescence of SMBBHs in FR II radio galaxies leads to the formation of DDRGs. This implies that X-shaped FR II radio galaxies forms ahead of DDRGs on a viscous time scale  $t_{\text{acc}} \sim 10^8$  yr. We applied the configuration to the DDRG J0116-473 which also shows a bar-like feature much older than the relic outer lobes. If we suggest that the bar-like feature in J0116-473 form due to the refill with back-flow radio plasma of the cavities in IGM excavated by the past plasma jet, the observations imply that the merger is minor with a mass ratio  $q \sim 0.1$ .

We divided FRI radio sources into three subclasses according to the different relation to FR II radio galaxies. Class I FRI radio sources are evolved from FR II radio sources before the interaction of accretion disk and SMMBHs. As in this subclass the stage of FR II phase is shorter than the average life time of most FR II radio galaxies, it may be expected that the average size is shorter than that of FR II radio sources. While Class III FRI radio sources form after SMBBHs get merged and relativistic jets restarts with lower power, the average size of the subclass is determined by the recurrent jets and is also expected to be smaller than that of FR II radio sources. One expectation is that it is possible to detect relic of outer giant radio lobes in some FRI radio sources, which should be aligned with the inner active radio lobes. If  $t_{\text{acc}} \ll t_{\text{relic}}$ , one may even detect a third pair of outer lobes with oldest age and S-shaped structure. From Eq. (23), this implies that  $q \ll 10^{-2} \dot{m}_{-2} (t_{\text{relic}}/10^7 \text{ yr})$ . Such triple pairs of radio lobes may have been detected in the nearest AGN Cen A (NGC5128) (Israel 1998). However, to compare the observation of Cen A and the model in more detail, we need the estimates of ages of the lobes.

Our model implies that Class I and Class II FRI radio galaxies and FR II radio galaxies with random jet orientation with respect to the galactic plane harbor SMBBHs with separation of  $10^2 r_G \lesssim a \lesssim 10^3 r_G$ . A close binary of  $a < a_{\text{cr}} \sim 10^2 r_G$  is a source of gravitational radiation. The coalescence of SMBBHs can produce an enormous burst of gravitational radiation. As the orbital plane of binary of  $a < a_{\text{cr}} \sim 10^2 r_G$  is coplanar with the accretion disk and the system is old, it may be expected to detect in low luminous FR II radio sources

with jets nearly vertical to the galactic disk close binary, which gives rise strong gravitational wave radiation and would be good targets for the monitoring of gravitational wave interferometers, e.g. LISA. Although the FRII radio galaxies in which binary merged also shows vertical radio jets, it is easy to distinguish them from the former subclass of FRII radio galaxies as they may have passed through the DDRG phase and contain giant relic of outer radio lobes.

No X-shaped structure is observed in high luminosity FRII radio galaxies and QSOs, which may be due to selection effect (Dennett-Thorpe *et al.* 2002). The accretion may be at the Eddington accretion rate  $\dot{m} \sim 1$  and the accretion disk is slim but not standard in QSOs. From Eqs. (12) and (42), we have  $t_{\text{bd}} \simeq 14t_{\text{d}}\alpha_{-1}^{4/5}\dot{m}^{2/5}M_8^{0.06}q_{-1}^{-3/4.02} \gg 1$ , which implies that the missing of high luminous FRII radio galaxies and QSOs may be due to no binary-disk interaction during the phase of high accretion rate. In the QSO, it is expected that the jets are nearly aligned with the minor axis of host galaxy. If the binary interacts with accretion disk during the phase of QSO and luminous radio galaxies, the transfer of warp is in a wave-like way and the time scales  $t_{\text{al1}}$  and  $t_{\text{al2}}$  are smaller than with those given by Eq. (9) and (25), leading to a rapid reorientation of jet in QSO. Since the time scale  $t_{\text{al3}} \sim 4 \times 10^6 \text{ yr}$  is too short for the jet to form a large scale X-shaped structure, we could detect distorted radio jet in QSOs and luminous radio galaxies.

## ACKNOWLEDGMENTS

We thank Dr. Z.H. Fan for helpful comments and Prof. D.N.C. Lin and Prof. X.-B. Wu for pleasant discussions. This work is supported by the National Natural Science Foundation of China (NSFC 10203001) and the National Key Project on Fundamental Researches (TG 1999075403).

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